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How to Form (Twin) Globular Clusters?

Christian Theis

Institut f. Theoretische Physik und Astrophysik, Universität Kiel, 24098 Kiel, Germany, email: theis@astrophysik.uni-kiel.de

Abstract. Though it is generally assumed that massive molecular clouds are the progenitors of globular clusters, their detailed formation mechanism is still unclear. Standard scenarios based on the collapse of a smooth matter distribution suffer from strong requirements with respect to cluster formation time scale, binding energy and star formation efficiency. An alternative model assuming cluster formation due to the recollapse of a supernova-induced, fragmented shell can relax these difficulties.

In this paper the final collapse stages of the different scenarios are compared by N-body simulations for shells and spheres. It is shown that fragmentation is much more pronounced for shells. Taking a galactic tidal field into account shells preferably form twin (or multiple) systems, whereas spheres end up as single clusters. The twins are characterized by identical metallicities, and stellar mass functions; some of them show counter-rotating cores. Their orbital evolution can result in both, a final merger or well separated twins sharing a common galactic orbit.

1. Introduction

Most formation scenarios of globular clusters commence with giant molecular clouds (GMCs) undergoing a phase of rapid star formation. This star formation can be triggered by several processes, e.g. a thermal instability (Fall & Rees 1985; Murray & Lin 1990), a radiative shock (Kang et al. 1990; Shapiro 1993) or other perturbations like collisions of clouds (Fujimoto & Kumai 1997; Lee, Schramm, & Mathews 1995) or galaxy interactions (Ashman & Zepf 1992). A common characteristic of all these scenarios is, that globulars are formed from smooth gaseous distributions (if we neglect the clumpy structure of the GMCs for the moment) which are transformed into stars. This assumption leads to several difficulties: First, the gravitational binding energy of a homogeneous GMC with $10^6 M_\odot$ and a radius of 30 pc is about $2 \cdot 10^{51}$ ergs, whereas it decreases for a $10^5 M_\odot$ cloud of 10 pc to less than 10^{50} ergs. Thus, already a single supernova injects sufficient energy to destroy a small cloud completely, and a few OB stars can even disrupt a $10^6 M_\odot$ cloud. Therefore, the formation of the globular must have been finished within a few Myrs, before the first OB stars explode. A second problem is related to the star formation efficiency (SFE). Assuming that the GMC is in virial equilibrium prior to the cluster formation and that the newly born stars keep the velocity of their parent gas packages, the total energy E of the stellar system can be estimated by $E = (1/2\eta - \eta^2) \cdot GM^2/R$ (with the

GMC mass M, its radius R and the gravitational constant G). Thus, the system is only gravitationally bound (i.e. E becomes negative), if the SFE η, which is the mass fraction of the GMC transformed into stars, is larger than 50%. Though mass redistribution in a violent relaxation stage and a detailed treatment of the energy injection can reduce the critical level down to 20% (Goodwin 1997), the required SFE still exceeds the typical observed values for GMCs by at least one order of magnitude (Blitz 1993).

With respect to these problems, an alternative suggestion by Brown, Burkert, & Truran (1991) is very interesting: They suggest that cluster formation starts with an OB-association undergoing typeII supernova events near the center of a molecular cloud. The expanding supernova remnant sweeps up the cloud material, decelerates and might almost be stopped by the external pressure of the ambient hot gas. Meanwhile the shell breaks into fragments and forms stars. If the total energy of this stellar shell is negative, the stars will recollapse and form a bound system. For a simplified spherical configuration Burkert, Brown, & Truran (1993) demonstrated that the binding energy of an isolated shell always becomes negative *independent* of the SFE, provided the star formation process does not start too early. Thus, the SFE efficiency problem is less severe for this scenario. In case of an homogeneous ambient medium (e.g. in the core of a GMC) Ehlerová et al. (1997) demonstrated that fragmentation in an expanding shell takes sufficient time to prevent too rapid star formation. This result holds also for non-homogeneous power-law density profiles, if the density distribution in the GMC is not steeper than isothermal (Theis et al. 1998).

According to the shell-scenario the dynamics of its last stage, i.e. the collapse of a thin stellar shell, is studied and compared with the collapse of homogeneous spheres representing the standard scenarios. N-body simulations are performed for isolated configurations as well as for collapses within a galactic tidal field. The main question addressed here is, whether we can discern between different formation scenarios by means of their collapse dynamics.

2. The evolution of an isolated shell

Initial conditions and numerical scheme. The shell is modelled by a unit mass which is homogeneously distributed within the radial range [0.9,1.0] giving a shell thickness of 10% of the shell's radius R. Initially the shell is at rest. The individual velocities of the equal mass particles are chosen from an isotropic velocity distribution resulting in a virial coefficient $\eta_{\rm vir} \equiv 2T/|W| = 0.05$ (T is the kinetic and W the potential energy.). The simulations are performed with $N = 100\,000$ particles adopting a softening length ϵ of 0.01. The equations of motion are integrated with a leap-frog scheme using a fixed timestep Δt of 10^{-3}. This gives an energy conservation of typically 0.1-0.2% or better over the whole integration time. The simulations were performed either with a direct summation code (using a GRAPE3af board) or a TREE-code.

Results. The dynamics of the shell shows three stages. During the first stage ($t < \tau_{\rm ff}(\rho_{\rm sh})$) the shell is slowly contracting and small inhomogeneities start to grow (cf. also upper left diagram in Fig. 1; $\tau_{\rm ff}(\rho) \equiv [3\pi/(32G\rho)]^{1/2}$ is the free-fall time corresponding to the mass density ρ). Already during this early stage the particles in the shell are strongly mixed because of the radially *decreasing* (global) free-fall time in the shell. In the second phase ($\tau_{\rm ff}(\rho_{\rm sh}) < t < 1 - 2\tau_{\rm ff}(\text{shell})$) the inhomogeneities become bound clumps. They merge after the shell's free-fall time $\tau_{\rm ff}(\text{shell}) \sim 1.59$ which exceeds the free-fall time of the corresponding sphere by 40%. Finally, a radially anisotropic triaxial system is formed.

The final configuration of the shell simulations is characterized by a more flattened shape, a mass-loss of only 8% (i.e. a reduction by a factor of 3.5), a smaller anisotropy $1 - \sigma_\theta^2/\sigma_r^2$, an increased half-mass radius (by 50%) and a decreased 90% Lagrange radius (factor of 6) compared to the corresponding collapse of a sphere. Thus, violent relaxation is less efficient in case of collapsing shells.

3. The evolution in a galactic tidal field

A realistic model should also include the galactic tidal field. Therefore, the gravitational force of a static isothermal halo with a circular velocity of 220 kms^{-1} is added to the force derived from the self-gravity of the N-body configurations. In all following models the galactic orbits have an apogalacticon of 5 kpc and the clusters start with a mass of $10^5 M_\odot$ and a size of 30 pc. At apogalacticon this corresponds to a tidal radius of 42 pc, i.e. systems on circular orbits are not expected to be tidally disrupted.

Circular Orbit. Though circular orbits are not very realistic for globular clusters, they keep the tidal field almost time-independent which allows a more direct investigation of the influence of the host galaxy. Fig. 1 shows the evolution of the system projected onto the orbital plane (and normalized to the center of mass of the particles in the collapsing system) for both, a shell and a sphere. Similarly to the isolated case, we find a strong fragmentation prior to the collapse of the whole system in case of the shell, whereas almost no substructure is seen during the collapse of the sphere. Lateron, the sphere forms a single bound object which shows immediately after the collapse some elongation caused by the tidal field. After one revolution around the galactic center, however, the system is almost spherical. In case of the shell, the influence of the tidal field is already obvious in the distortion prior to the collapse. The delayed collapse, the fragmentation and also the reduced violent relaxation leads to a less dense system which is much stronger affected by the galactic tidal field: The system does not merge into a single object, but into two (twin) stellar systems of almost identical total mass and density distribution. However, in their kinematical properties both objects differ: one of the clusters shows a counter-rotating core which is neither found in the second 'twin' nor in the product of the collapsing sphere.

Eccentric Orbit. On eccentric orbits the evolution additionally depends on the initial phase (Fig. 2). A collapse of a shell starting at apogalacticon ends up again in a twin cluster (a in Fig. 2). If the phase is chosen such that maximum compression is reached at perigalacticon (b), the system breaks up into many small systems, but no large cluster is formed. When the collapse starts at perigalacticon even the formation of these small clusters is prevented (c). If the collapse starts well after perigalacticon a multiple system of clusters (with two larger ones) is built up (d). The final fate of the twins is less clear: the

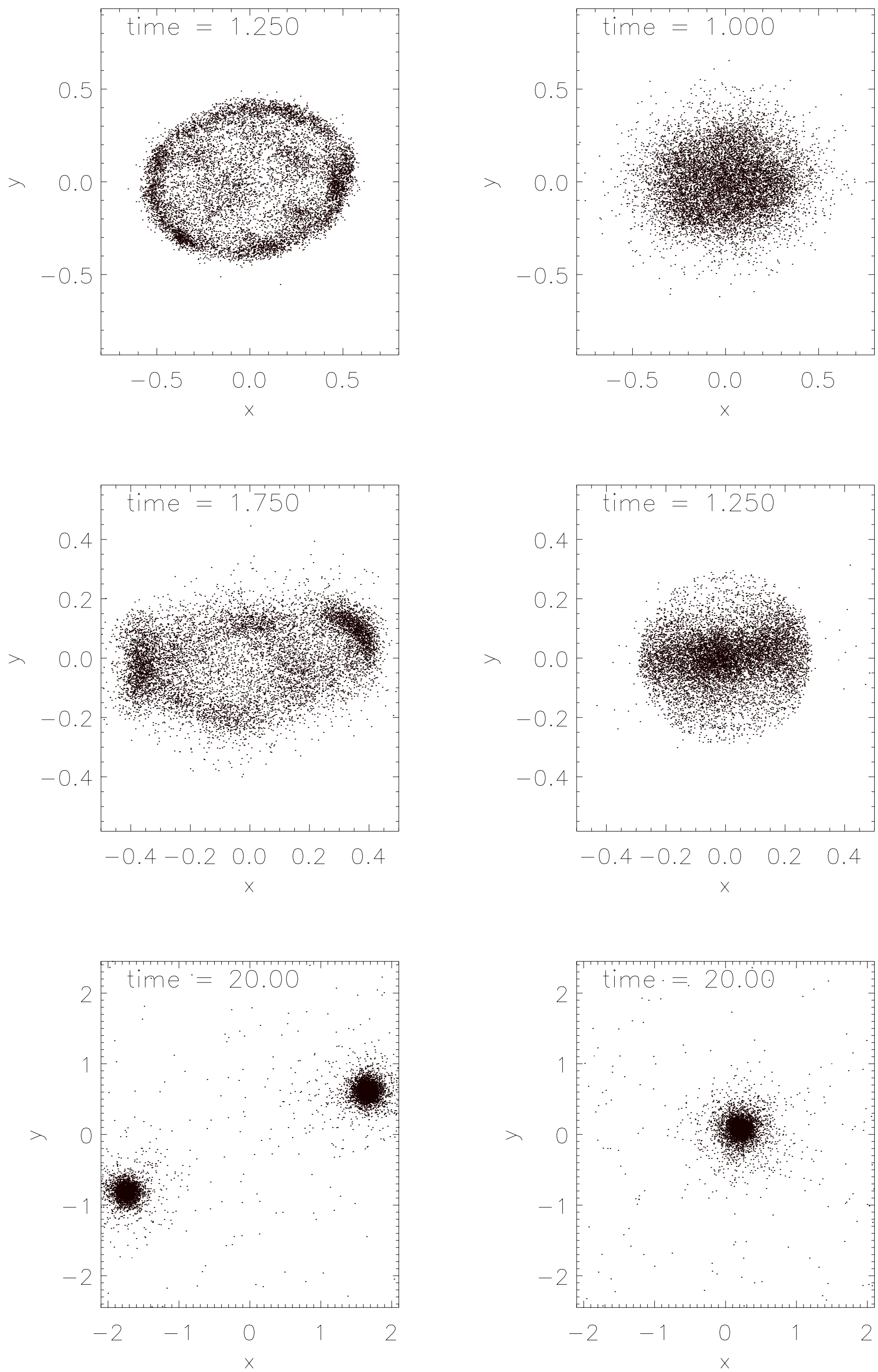


Figure 1. Projections of a collapsing shell (left column) and a collapsing sphere (right column) on the orbital plane at different times: a) prior to the collapse (upper row), briefly after the collapse (middle row) and in the final stage. The units are 7.7 Myrs and 30 pc. Note that the free-fall time for the shell is ~ 1.59 in the given units, whereas the sphere collapses within $t \approx 1.11$.

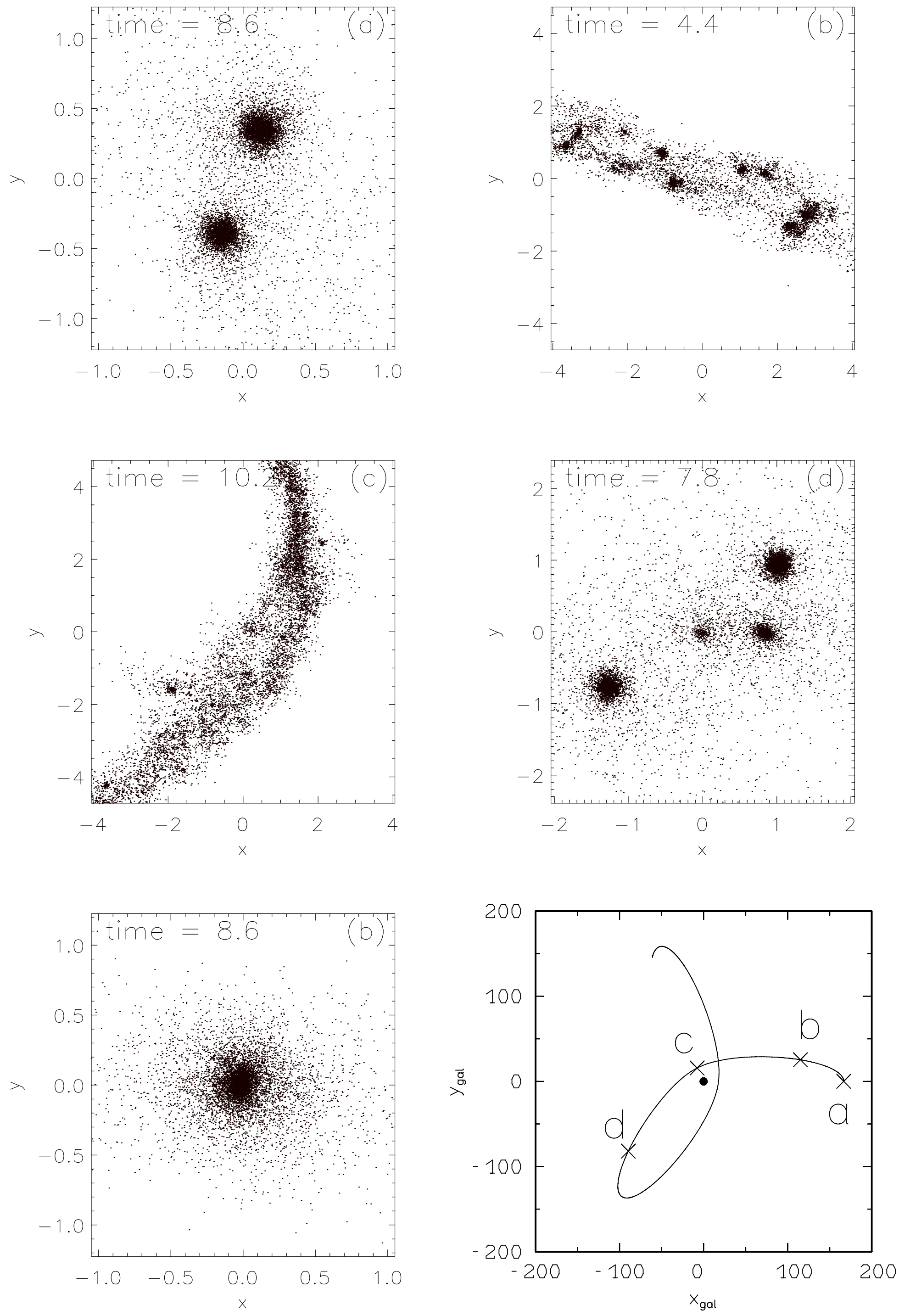


Figure 2. Evolution of shells starting to collapse at different phases on an elliptic orbit (upper two rows). The starting points are shown in the lower right panel. The lower left diagram displays the final state of an initial sphere which starts at location b. Units and tidal field are identical to Fig. 1.

simulations show preferably surviving twins which separate after a few orbital revolutions to distances of several 100 pc up to kpc scale or more. However, also merging twins have been found. The low number statistics of the simulations performed so far does not allow to give more accurate rates here. Contrary to the shells the spheres do not form any multiple clusters: either the systems are completely destroyed or single bound objects are formed.

4. Summary

In case of isolated evolution the simulations show several systematic differences between shells and spheres: The collapse of the shell is delayed, the resulting configurations are flatter and (more) triaxial, the mass-loss is strongly reduced and the system is less dense. All of these effects suggest that *violent relaxation* is less efficient for collapsing shells. Another difference is the strongly pronounced fragmentation of the shell which is not seen during the collapse of the sphere. Unfortunately, all of these features seem to be very difficult to be used for an observational discrimination between the different formation scenarios. E.g. the easy accessible flattening of globular clusters is not only strongly influenced by the formation scenario, but also by the secular evolution, the galactic tidal field, and by initial conditions like the mass distribution in the parent GMC and the virial ratio of the collapsing stellar system.

Much more promising are the simulations including a galactic tidal field: They demonstrated that shells tend to form multiple stellar systems, preferably twin (but not binary) clusters. In case these twins are not destroyed nor merged, one should be able to find pairs of globular clusters which are characterized by the properties of their common birth place, i.e. identical metallicities and evolutionary stage or similar orbital characteristics. Another observational feature is the rotation profile of globulars. The merging of fragments in the shell scenario would give a natural explanation for counter-rotation in stellar clusters similar to the counter-rotation found in N-body simulations of merging galaxies.

A set of movies is available at http://www.astrophysik.uni-kiel.de/pershome/theis

References

Ashman, K.M., Zepf, S.E. 1992, ApJ, 384, 50

Blitz, L. 1993, in Protostars and Planets III, E.H. Levy & J.I. Lunine (eds.), 125

Brown, J.H., Burkert, A., & Truran, J.W. 1991, ApJ, 376, 115

Burkert, A., Brown, J., & Truran, J.W. 1993, in The Globular Cluster-Galaxy Connection, ASP Conf. Ser. Vol. 48, Graeme H. Smith, Jean P. Brodie (eds.), 656

Ehlerová, S., Palouš, J., Theis, Ch., & Hensler, G. 1997, A&A, 328, 121

Fall, S.M., Rees, M.J. 1985, ApJ, 298, 18

Fujimoto, M., Kumai, Y. 1997, AJ, 113, 249

Goodwin, S. 1997, MNRAS, 284, 785

Kang, H., Shapiro, P.R., Fall, M., & Rees, M.J. 1990, ApJ, 363, 488

Lee, S., Schramm, D.N., & Mathews, G.J. 1995, ApJ, 449, 616

Murray, S.D., Lin, D.N.C. 1990, ApJ, 363, 50

Shapiro, P.R. 1993, in The Globular Cluster-Galaxy Connection, ASP Conf. Ser. Vol. 48, Graeme H. Smith, Jean P. Brodie (eds.), 664

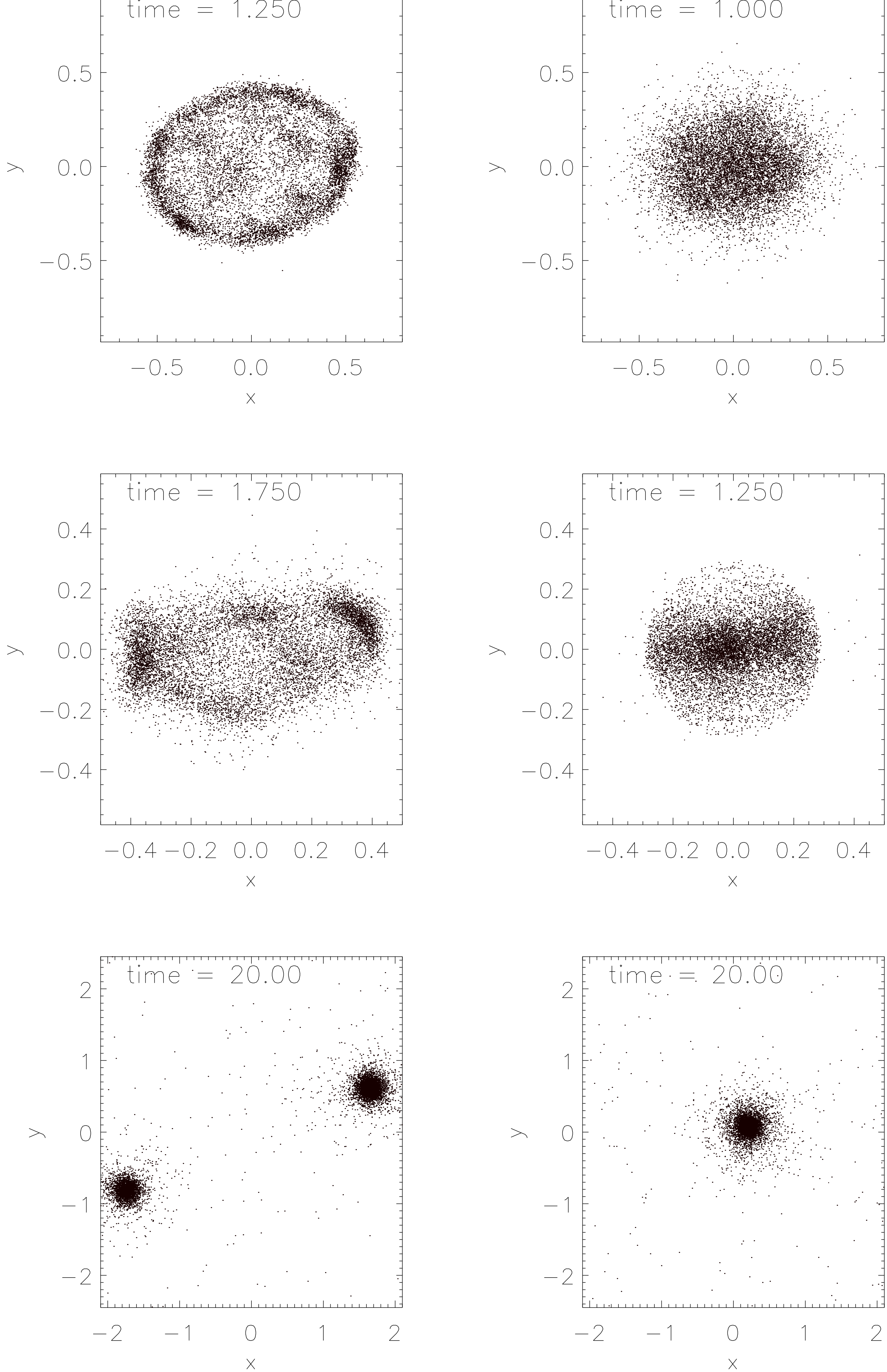
Theis, Ch., Ehlerová, S., Palouš, J., & Hensler, G. 1998, in The Local Bubble and Beyond, IAU Coll. 166, D. Breitschwerdt, M.J. Freyberg, J. Trümper (eds.), 409

Ivan King: This is fascinating material. Two Questions: 1) How much anisotropy is there in your aspherical collapse products? 2) Can you make your animations available, perhaps as mpegs in your anonymous ftp?

Christian Theis: 1) The velocity distributions of both, spheres and shells, are isotropic in the central regions. In the outer region a radial anisotropy (defined here as $1-\sigma_\theta^2/\sigma_r^2$) evolves reaching about 0.8 in case of the shell. It is systematically below the anisotropy of the sphere by about 0.15. 2) The animations are available via my home-page http://www.astrophysik.uni-kiel.de/pershome/theis

Christian Boily: 1) Why is there no ROI developing in the spherical collapse you showed? 2) Presumably fragmentation here depends on $\sqrt{N}$ noise. What were the numbers involved here?

Christian Theis: 1) The initial virial coefficient here is close to, but exceeding the limit for the onset of the radial orbit instability for my simulations. Starting from a lower virial ratio of e.g. 0.02 shows the ROI for the collapsing spheres as expected.
2) The fragmentation depends partly on the number of particles and and also on the initial setup of the particle configuration (here a random realization, i.e. white noise). The total number of particles was 10^5. However, the most important parameters for the onset of fragmentation are the velocity dispersion in the shell and its thickness. E.g. a thickness of 50% or an initial virial ratio of 0.2 strongly suppresses fragmentation.



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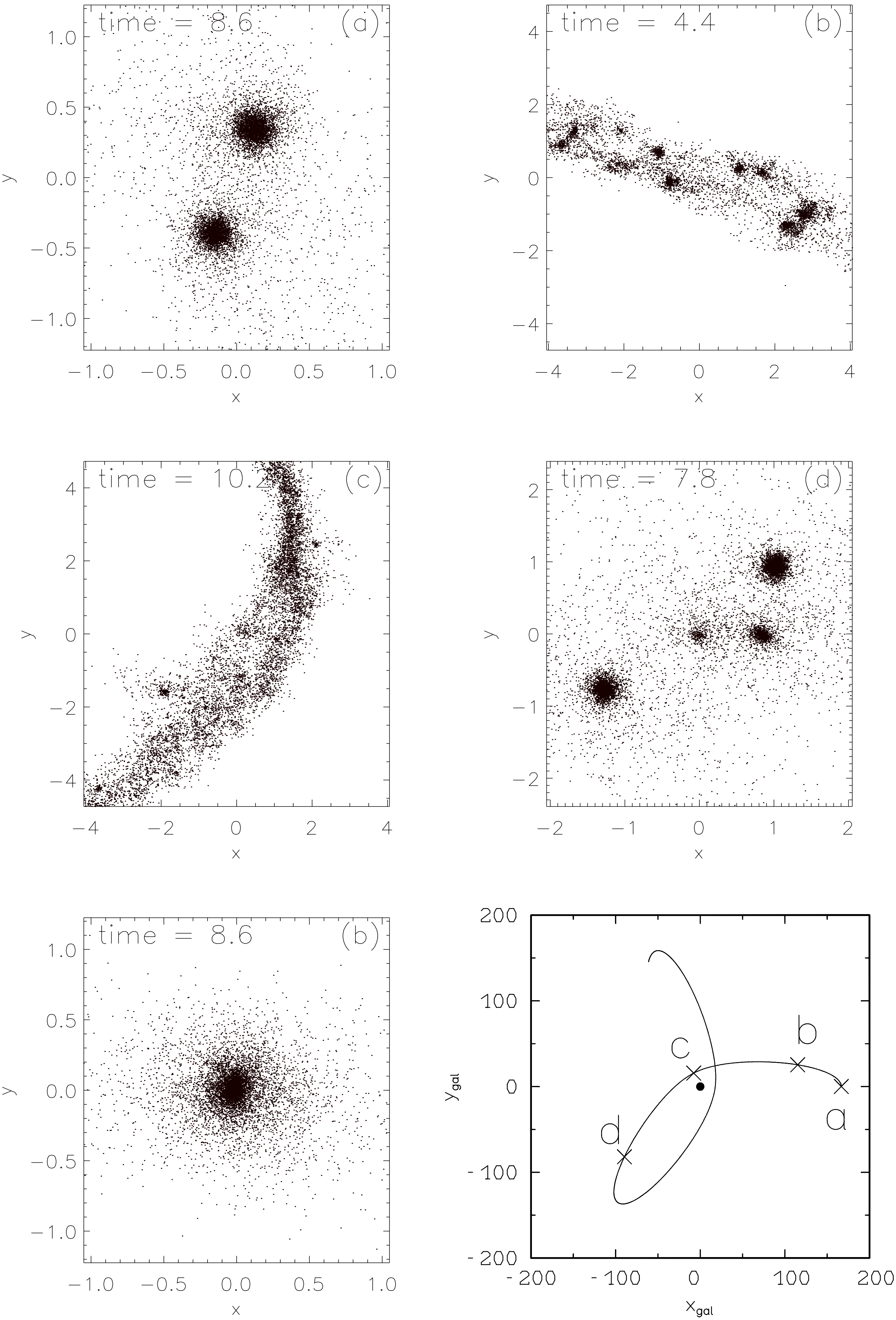

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(a)
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(c)
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(d)
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